Reactor Boiler and Auxiliaries - Course 133

THE FUNCTIONS OF REACTIVITY MECHANISMS

The reactivity mechanisms, in a reactor, represent the final control element which causes a change in the neutron multiplication factor, k, or the reactivity δk. There are three general requirements of a control system:

1. It must keep $k = 1$ and $\delta k = 0$ during steady power operation, so that it must compensate for changes in reactivity that occur due to fuel burnup, poison buildup and temperature changes.
2. It must allow δk to become positive or negative in order to change reactor power at the required rate.
3. It must decrease k sufficiently, or provide a large negative δk value, for rapid shutdown of the reactor when this is required.

It is neither desirable nor convenient for these three functions to be executed by the same system. There are, therefore, two systems which are, preferably, entirely independent:

(a) The regulating system which regulates the value of k as required in (1) and (2) above.

(b) The protective system which provides the large negative reactivity for a rapid reactor shutdown as in (3) above.

The reactivity mechanisms used as the final control element in the two systems may also be entirely separate and independent. However, some reactivity mechanisms may serve both purposes.

A reactivity mechanism, used for regulation, must always be capable of providing a reactivity change larger than the following:

1. The random and short-term reactivity variations due to refuelling or temperature changes in the moderator, heat transport fluid and fuel.
2. The long-term variation of reactivity due to fuel burnup.
3. The large excess reactivity in the reactor because of the low fission-product poison level with fresh fuel or at startup following a long shutdown.

4. The reactivity decrease during the first 30 to 45 minutes of the xenon transient which follows a reactor shutdown or power reduction.

The regulating system may also be required to control the neutron flux distribution in the reactor. Heat transport fluid flow through each fuel channel is regulated to give the same exit temperature for all channels with the expected flux and power distribution in the reactor. If the temperature is the maximum achievable without overheating the fuel, such a condition represents the maximum efficiency of energy transportation to the turbine. Under these conditions any distortion of the flux and, therefore, of the power will cause some of the fuel to be overrated unless the total power is reduced. Such total power reductions can be avoided if reactivity mechanisms are used to decrease the reactivity locally where excessive power is being produced and, thus, reduce the power in that region. Such flux and power distortions may well be caused, or at least amplified, by xenon oscillations. Regional flux control by independent reactivity mechanisms is essential if xenon oscillations are likely to occur.

Protective reactivity mechanisms must provide a large reactivity load (ie, negative reactivity) for rapid shutdown. The rate at which this negative reactivity is introduced, as well as its total value, must compensate for the total reactivity increases possible as a result of malfunction of a process system such as the regulating or heat transport systems.

Before the reactivity mechanisms are compared, further consideration should be given the reactivity variations which have to be controlled.

Possible Reactivity Variations

The random and short-term reactivity variations are most frequently caused or connected with on-power refuelling. Burnt or depleted fuel must be replaced so that the fissile atom concentration is sufficient to maintain a chain reaction. Liquid fuel can be continuously replenished so that the correct fissile atom concentration is maintained. Such liquid fuel systems are not yet practical. Solid fuel must be changed discontinuously. After each refuelling operation the fissile atom concentration is excessive and must be compensated for by increasing the reactivity load, ie, by removing excess neutrons not required to maintain the chain reaction. The fissile atom concentration then returns to the required value just before the next refuelling and the reactivity load must be correspondingly reduced during this period.

With on-power fuelling the normal reactivity change during refuelling is small (less than 0.15 mk in Pickering) and the rate of change of reactivity is also small (less than 0.1 mk per second in Pickering). The replacement of all the fuel bundles with new fuel in a central channel would result in a reactivity increase of 0.5 mk in Douglas Point and 0.22 mk in Pickering. The rate of reduction of reactivity, in either reactor, with no refuelling is about 0.4 mk per day. These reactivity changes and rates of change are compensated for without difficulty.

In reactors which cannot be refuelled on power, the refuelling frequency will not be greater than once every six months. Each refuelling then results in a large increase in reactivity. The compensating reactivity load must be decreased over a short period of time to allow for poison buildup and it must be decreased over an extended period of time to allow for fuel burnup.

Little change in moderator temperature should normally be expected unless there is a change in the efficiency of the heat removal system. However, substantial changes occur in the fuel and heat transport fluid temperatures due to changes in reactor power. The power coefficient of reactivity is usually negative for stability and because of safety requirements. Thus, an increase in power causes a decrease in reactivity. In Douglas Point an increase from zero to full power causes a 5.3 mk decrease in reactivity. A compensating reactivity load must, therefore, be inserted, at low power, which can be removed as reactor power increases.

With initial fuel in Douglas Point, at zero power, an increase of heat transport fluid temperature to 504°F causes a decrease of 7 mk in reactivity.

The long-term variations of reactivity with burnup are generally much greater than those discussed above. For instance, in Douglas Point there is a decrease of 55 mk from the initial fuel charge to the equilibrium fuel condition, assuming equilibrium xenon in both cases. The equilibrium xenon load is also large compared to the values above being about 28 mk in both Pickering and Douglas Point. Thus a reactor with fresh clean fuel would have an excess reactivity of 82 mk compared to an equilibrium core with equilibrium zenon load.

Since the maximum xenon transient load is more than double the equilibrium load, it is not practical to have enough excess reactivity in the reactor to avoid a poison-out altogether. Normally, enough excess reactivity is available to provide a poison override time of about 45 minutes. The rate of growth of the xenon load in Douglas Point and Pickering, following a reactor shutdown from full power, is about 23 mk per hour. Thus, in 45 minutes the xenon load will have increased by about 16 mk.

It may be seen from the above considerations that there are three classes of reactivity variations which have to be considered:

(a) Small reactivity variations as a result of refuelling or temperature changes.

(b) The xenon transient load increase during the poison override time.

(c) The large decreases in reactivity due to such things as equilibrium poison buildup and long-term fuel burnup.

There is one overriding consideration and that is the necessity of regional control to prevent flux and power distortions due to xenon oscillations.

Types of Reactivity Mechanisms

All reactivity mechanisms either increase neutron production or decrease neutron losses in order to change the value of k. Neutron production can be increased by addition of fissile material. Neutron losses can be changed by:

(a) Changing neutron absorption in materials other than the fissile material. This can be done in a variety of ways:

    1. By inserting or removing neutron absorbers into or out of the reactor core.

    2. By changing the moderator density so that a change occurs in the absorption by nonfissile fuel nuclei.

(b) Changing neutron leakage out of the reactor either by:

    1. Changing core size or

    2. Changing reflector thickness.

It is clear that one type of reactivity mechanism, relying on one of the above methods of reactivity variations, could not meet all the regulation requirements discussed previously. It would be even less likely to meet the protective system requirement as well. Thus, several types of reactivity mechanisms would be used in the same reactor and these could be classified as to types and functions as follows:

(a) BOOSTER MECHANISMS which would be used to increase reactivity, during xenon transients, to provide the required poison override time. Such booster mechanisms could be:

1. Absorbers, such as Cobalt rods, which are in the reactor during normal operation and are removed to reduce neutron losses during a xenon transient.

2. Additional fuel rods which are inserted into the reactor only when required for additional reactivity during a xenon transient.

(b) Variable REACTIVITY LOADS to compensate for small variations in reactivity. Since such reactivity loads must be continuously variable during reactor operation, they must depend on a continuously variable neutron removal system such as:

1. Variable neutron leakage achieved by variable moderator-reflector level which varies the core size or the reflector thickness above the core.

2. Variable moderator temperature to vary neutron leakage and relative neutron absorption in nonfissile fuel material.

3. Variable moderator density, such as obtained by bubbling a gas through it, to achieve the same results as in (2).

4. Variable neutron absorbers in the core.

(c) POISON SYSTEMS to simulate equilibrium fuel conditions or equilibrium xenon loads in a reactor in which sufficient excess reactivity has been provided to compensate for fuel burnup and xenon buildup to equilibrium. This is known as SHIM control.

(d) SHUTDOWN MECHANISMS to provide the large negative reactivities required following a reactor trip. Such large negative reactivities can be obtained by:

1. Dumping the moderator, if it is a liquid, and thus greatly increase neutron leakage, or

2. Inserting absorber, known as SAFETY or SHUT-OFF RODS.

ASSIGNMENT

1. Distinguish between the functions of the regulating and protective systems.
2. What five requirements are demanded from reactivity mechanisms used for regulation?
3. Why is it not possible for one type of reactivity mechanism to meet all the requirements in (2)?
4. Explain the four types of reactivity mechanisms that can be used to meet the regulating and protective system requirements.

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